Propagation Models for Predicting Communication System Performance in Tunnels, Caves, and Urban Canyons

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This project addresses the problem of characterizing the propagation of electromagnetic fields in the adverse environments that are encountered in enclosures such as caves and tunnels, where rough surface can compromise the quality of signals.

Project Goals

We have investigated the propagation physics; developed the mathematical models; derived the statistical descriptors, specialized to radio communication in tunnels and caves; and selected the models/methods best suited to the parameter space describing enclosures of interest.

Relevance to LLNL Mission

A military or emergency response commander must see, understand, and interact with complex environments such as caves and tunnels in "real time," and both receive and feed tactical data among the individual soldier, policeman, firefighter, and command post. This must be done from local or remote sensors. It is not possible to predict when wireless communications systems will be useful and when they will fail. A predictive tool is needed, to allow planning and preparation of communications systems.

To do this, we need to go beyond oversimplified empirical models of RF propagation in complex environments. Such models base their statistics on experiments without sufficient underlying theory to enable generalization to environments other than those in which the experiments were conducted.

The Yucca Mountain Repository Project, for example, requires reliable wireless communications systems for 300 years at the underground structure. This project is intended to fulfill this requirement.

An accurate model for a wireless propagation channel matches both the national security and the energy missions of the Laboratory.

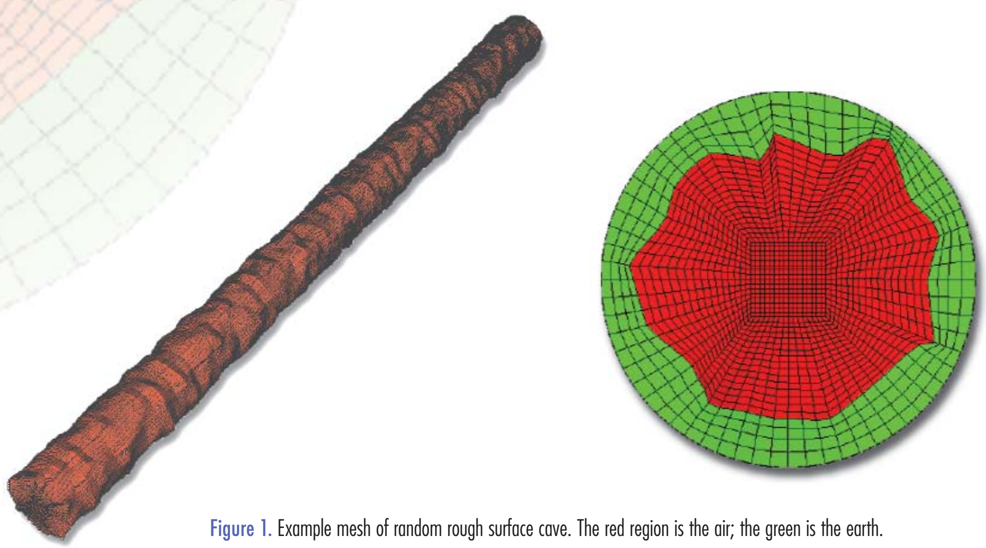

Figure 1. Example mesh of random rough surface cave. The red region is the air; the green is the earth.

FY2004 Accomplishments and Results

Our analytical work during FY2004 focused on specific problems: investigating the excitation and propagation of electromagnetic fields excited by sources situated within straight caves and tunnels that have rough walls (see Fig. 1); deriving the statistical characteristics of the fields and signals of RF in straight, perfect electrical conductor (PEC) rough wall tunnels; and extracting the wireless communication channel model in the tunnel from the physics-based models.

The principal results are as follows.

First, the field is shown to comprise the sum of a coherent or deterministic part and a zero-mean incoherent or random part. The latter is described by the appropriate correlation functions. Representative analytical and numerical results for the case in which the source is an electric-current loop show that the random part of the axial magnetic field is proportional to the deterministic part of this field, and is bound to the rough wall of the tunnel. The tightness of the binding is dependent on the signal frequency, the tunnel radius, and the power spectral density of the wall roughness.

Second, the probability density function for single-mode field-amplitude propagating in a straight PEC rough wall cave or tunnel is Ricean. Its distribution function is given by the analytic form consisting of exponential, power and modified Bessel function. The probability density function for the phase of single-mode field in the cave or tunnel is of analytic form as well. The expected values of the single-mode field-amplitude and intensity are derived. They represent the deterministic parts of single-mode field amplitude and intensity, respectively, and have very simple mathematical forms.

Third, the probability density function for total field amplitude in the cave or tunnel are Gaussian distributed. The probability distribution functions are the error functions. The average total field amplitude and intensity are of simple analytic mathematic forms.

Figures 2 and 3 show representative probability functions.

Fourth, field strength versus axial distance in tunnels can be divided into two regions. For near distances, the model has an axial dependence on z. For greater distances, the model produces an exponential axial fall-off, where the rate of decay is governed by the wavenumber of the dominant guided wave mode.

Our work has led to numerous presentations and publications.

Related References

1. Dudley, D. G., "Wireless Propagation in Circular Tunnels," *IEEE Transactions on Antennas and Propagation*, in press.

2. Pao, H., "Probability Density Function for Wave Propagation in a Straight PEC Rough Wall Tunnel," *Microwave and Optical Technology Letters*, in press.

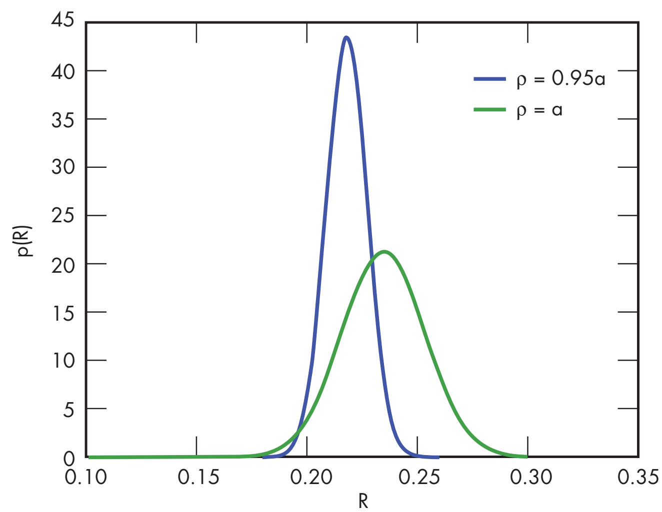

Figure 2. Probability density function for TE_{11} and TM_{01} modes at different radial locations.

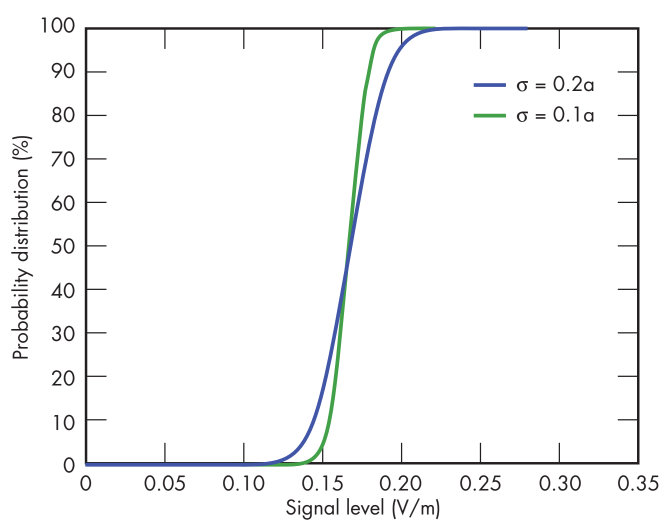

Figure 3. Cumulative probability distribution function for the amplitude of single-mode random, field at different wall roughness.